

IS THE SUN A LONG PERIOD VARIABLE ?

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ABSTRACT

The inventory of atmospheric radiocarbon exhibits quasi-periodic variations of mean period of $\bar{\Lambda}_m = 269$ years over the entire 9000 year record. But the period is inconstant and subject to random variability ($\sigma_m^{1/2} = 119$ years). The radiocarbon maxima correspond to the quasiperiodic extension of the Maunder minimum throughout the Holocene and resolve the long-standing issue of Maunder cyclicity. The radiocarbon maxima are amplitude modulated by the ~ 2300 year period and thus vary significantly in peak value. The ~ 2300 year period in turn appears to not be modulated by the secular geomagnetic variation. Detection of a Maunder-like sequence of minima in tree ring growth of Bristlecone pine and its correlation with the Maunder [1890, 1922] cyclicity in the radiocarbon record supports the inference that solar forcing of the radiocarbon record is accompanied by a corresponding forcing of growth of timberline Bristlecone pine. Because of the random component of the Maunder period, prediction of climate if tied to the Maunder cycle, other than probabilistically, is significantly hindered. For the mean Maunder period of 269 years the probability is 67 % that a given climatic maximum lies anywhere between 150 and 388 years.

INTRODUCTION

We have analyzed a composite set of radiocarbon (^{14}C) records comprising a sequence extending from 7202 BC to 1900 AD together with a reappraisal of the Campito Mt. Bristlecone pine (*Pinus longaeva*) record of tree ring growth [La Marche and Harlan 1973]. The Bristlecone record has previously been reported to contain spectral features particularly at ~ 2000 and ~ 200 years correlated with the La Jolla radiocarbon sequence [Sonett and Suess, 1984]. Moreover, the cross-MEM spectrum of the two records shows non-zero coherence at these periods with the tree record leading by some 70-80 years [Sonett 1988]. Because this lag is in gross disagreement with the bomb-derived value between production and inventory of radiocarbon, we had not in the past strongly emphasized these results since the publication of Sonett and Suess. As it turns out this lag appears to be consistent with the negative correlation between Maunder minima recorded by radiocarbon and the Bristlecone pine. That the Bristlecone record shows a cyclicity record with some similarity to the 'Maunder cycles' of the radiocarbon record but correlated negatively with the radiocarbon record suggests, presupposing tree growth to vary directly with solar irradiance, that the Sun's long period variability is reflected into a climatic replication of the Maunder cycle. The Maunder cycle contains a strong stochastic (or chaotic) element which explains some of the difficulties encountered in past searches for simple harmonically related periods in the radiocarbon record.

THE DELTA RADIOCARBON SEQUENCE

The radiocarbon sequence reported here is composed of segments, sometimes overlapping, from records from Pearson? et [1986], Linick et al [1986], Kromer et al [1986], and Suess and Linick [unpublished]. To make up a continuous sequence we interleaved all records in ascending time. The composite sequence extends from 7202 BC-1900 AD.

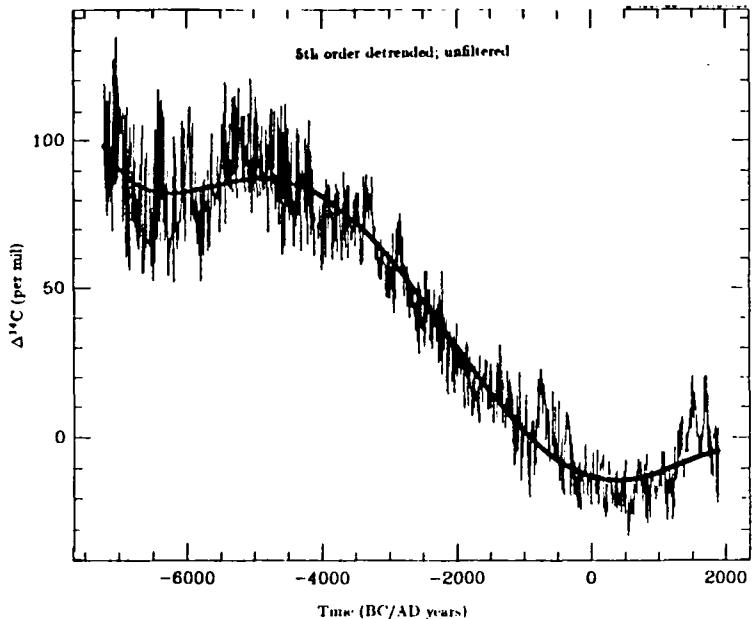


Fig. 1. Composite $\Delta^{14}\text{C}$ record (detailed in Table 1) with model 5th order detrend polynomial.

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The major trend shown in Fig. 1 is generally attributed to a nearly secular increase in the Earth's magnetic field [Buchta 1970; Barton et al 1979; McElhinney and Seneyake 1982; Creer 1988] (and has often been removed using a sinusoidal function). The recent extension of the chronology clearly shows the secondary minimum centered at about 6000 BC. This new addition requires a high order (5th) detrend fpr computation of the spectrum. The filtered, splined, and equally spaced $\Delta^{14}\text{C}$ sequence contains the complete spectrum of variations, including a very long period component identified with the $\Lambda_c \sim 2300$ year line.

For the primary matter at hand involving narrow banding the sequence, a numerical filter with Pascal distributed weights (filtering to ~ 100 years) is used. This is followed by subtraction of a low frequency version of the sequence obtained by passing the sequence through 99 point Pascal weights with cutoff ~ 1000 years. This yields the multi-hundred year response sequence (Fig. 2) which displays 34 maxima of varying amplitude; amplitude modulation of the signal has a period of approximately 2300 years, consistent with the low frequency line in the periodogram. There are a total of 34 radiocarbon maxima in Fig. 2 measured between positive peaks. Tests using varying thresholds disclosed that essentially all minima were incorporated into the search routine for the choice used. The maxima are taken to correspond to solar activity (Maunder) minima [Stuiver and Quay 1981]. Variable amplitudes are attributable to amplitude modulation (AM) of the signal by the $\Lambda_c \sim 2300$ year period. Maxima during the last millennium are much smaller than at 1300 AD. During the historical sunspot Maunder minimum, sunspot activity was zero or very small. If the 1300 AD radiocarbon maximum also infers a sunspot "zero" then the additional increment of radiocarbon, over and above what is necessary to explain a sunspot minimum, requires a modification of the atmospheric inventory with an increase in total carbon dioxide. In short, for radiocarbon increases over and above that associated with the historical Maunder period a climatically forced atmospheric CO_2 inventory change is inferred with radiocarbon a tracer of total carbon though most of this variability appears to be associated with the ~ 2300 year periodicity.

BRISTLECONE PINE SEQUENCE AND STATISTICS

The Campito Mt. Bristlecone record (3435 BC-1970 AD) [La Marche and Harlan 1973] from timberline in the White Mts. provides an absolute chronology of growth ring spacing [La Marche and Harlan 1973; La Marche 1974]. It is too long for efficient computation involving multi-hundred year periods, so we filtered it first by a 9 weight Pascal filter followed by narrow banding as for the radiocarbon. This sequence shows the same general properties as $\Delta^{14}\text{C}$. Tables 1a and b contain the statistics of the Maunder cycles for both radiocarbon and Bristlecone.

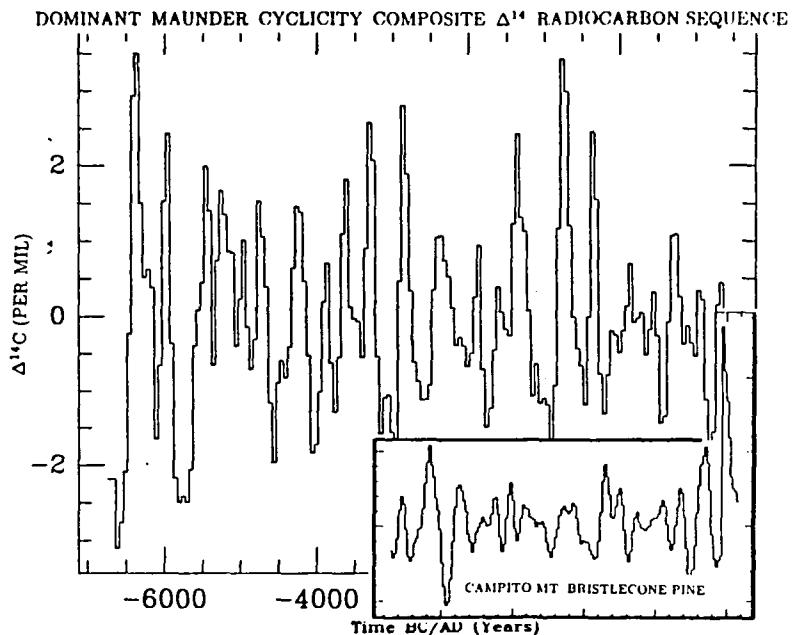


Fig. 2. $\Delta^{14}\text{C}$ narrow banded to emphasize the dominant period characterized by $\Lambda_m = 269$ years. 2300 year variability can be seen as an amplitude modulation of the sequence peaks; vestigial suggestion of ~ 1000 years is also present; (b) Inset: time sequence for Campito Mt. Bristlecone pine with narrow banding corresponding to the radiocarbon record of Fig. 1.

THE RADIOCARBON AND TREE RING SPECTRA

Detrended periodograms disclose complex spectra in the multi-hundred year and millennial range of periods for both sequences. Estimates of spectral line feature periods have been made using the Bayesian estimator of Brethorst [1988]. Apparently robust periods are present in the same approximate neighborhood (~ 200 and ~ 2300 years) for both sequences; however the cross MEM spectrum (Sonett and Suess 1984) shows a more convincing relation between the two sequences.

Table 1a. Radiocarbon derived Maunder statistics
maxima spacing statistics (years)¹

Moment (years)	Value (a)	Value (b)
Mean period	269	
Variance	119	
No. maxima	32	

¹ Based upon a lower search bound of -1 per mil of the heavily filtered data (See Fig. 2)

Table 1b. Bristlecone-derived Maunder statistics

Mean period	166
Variance	88
No. maxima	19

THE VERY LONG RADIOCARBON PERIOD

Both ^{10}Be and ^{14}C are produced by the CR flux, though production of ^{10}Be is via atmospheric spallations and is scavenged from the atmosphere in 2-3 years by attachment to aerosols [Raisbeck et al, 1981]. Since production of ^{14}C and ^{10}Be are coeval and ^{10}Be is rapidly stored it serves as an important CR proxy to radiocarbon. ^{10}Be exhibits 9-11.4 year variations as well as variability during the Maunder minimum. The Camp Century/Dome C composite ^{10}Be ice core record shows a remarkable though imperfect correlation inferring that the Maunder cycle is also present in the Be record [Beer and Raisbeck, in press]. The record of ^{10}Be is imperfect; evidence for a 2300 year period in the record of this isotope is uncertain at best and generally lacking. This supports the view that the 2300 year radiocarbon line is of terrestrial origin.

The periodicity of ca. 2300 years is also found in the $\delta^{18}\text{O}$ record in ice cores and foraminifera from ocean cores (Pestiaux et al, 1987; 1988). Glaciation shows this period as does the Middle Europe oak dendroclimatic record and Dansgaard et al (1984) report the most prominent period in their Camp Century $\delta^{18}\text{O}$ core to be a line at 2550 years. Early publications of Dansgaard's group discuss periodicities in the $\delta^{18}\text{O}$ record for the time interval from 1200-2000 AD (Johnsen et al. 1970; Dansgaard et al., 1971). Their chronology was based on the assumed average accumulation rate of ice, and their power spectrum for this time interval shows prominent periods at 78 and 181 years. They associate the 78 year period with the Gleissberg sunspot periodicity. In a longer section of the core going back to about 10,000 years, they obtain a period of 350 years, again using the ice accumulation time scale (ibid., 1971), and at about 45,000 BP ice accumulation rate years, they find a persistent oscillation with period of ~ 2000 years.

Can the source of the 2300 year period be isolated? It appears to be free of modulation by the $\sim 10,000$ year secular trend. If the 2300 year source were extraterrestrial, it should interact non-linearly with the secular trend since they are related through $Q \sim B^{-0.52}$ [Elsasser et al 1954]. No such effect has so far been detected. Moreover an extraterrestrial mechanism should have to be non-linear mechanism to account for its modulation of the 269 year period. This would not likely be seated in the solar wind which is adiabatic to both periods. Therefore the solar atmosphere becomes a prime candidate.

On the other hand characteristic deep water residence times for the global oceans range from 1,000 years for the Atlantic to 2,000 years for the full Atlantic-Pacific circulation [Broecker and Peng 1970; Broecker and Li 1970]. In themselves these delay times by themselves cannot explain the global ocean-atmosphere

resonance required to drive a 2300 year total CO₂ cycle, but the times are consistent with such a resonance. Yiou et al [in press] report periods, primarily Milankovich-derived from deuterium analysis of the Vostok ice core. It is noteworthy that periods at 4.4, 3.5, 2.7, and 2.4 kyears are detected. Their assignment of these is to harmonics arising from orbit-climate interactions. Sonett [1985], Sonett and Finney [in press], and Damon and Sonett [in press] find a 2.3 kyear period in radiocarbon (Damon and Sonett also report vestigial evidence of an \sim 4 kyear period using the Brethorst algorithm). It may never be possible to isolate the 2.3 kyear forcing with confidence. If due to orbit-insolation it may still drive global CO₂ and thus dilution of radiocarbon. If so a search for an ocean-atmosphere resonance independently of orbit-insolation may be meaningless.

CLIMATE AND THE PARTITION OF CARBON

Assuming that the Bristlecone record can be duplicated elsewhere a role for the Sun in climate is inferred; but it is complicated by the lack of understanding of how correlated bolometric and hydromagnetic mechanisms can coexist on the Sun. Moreover the bolometric component forces modification of the atmospheric CO₂ inventory through mediation of the ocean surface temperature and possibly other effects. The Natl. Academy [1975] report settles upon a 2.5° C temperature change per doubling of the CO₂ atmospheric inventory. Sensitivity studies of temperature vs. CO₂ are reported, e.g. by Hansen et al [1981] and Lal [1985] and point out the complications arising from sensitivity of the concentration to reservoir content. The atmospheric CO₂ inventory and radiocarbon concentration are jointly determined by CR flux and the terrestrial environment; partitioning of forcing of the net radiocarbon level between atmospheric dilution and CR production is uncertain because both the CR flux and terrestrial reservoir exchange are inconstant. A number of the spectral features found in the radiocarbon model have amplitudes of (O) 2.5 per mil. Using the Houtermans et al [1973] model for production and reservoir concentration values to establish a qualitative approximation, a 200 year period in production rate results in an attenuation in atmospheric disturbance \sim 20 times, depending upon transfer coefficients. Thus the interplanetary peak-peak variation is very approximately 2.5 %. For the 2300 year cycle attenuation is nil. For a steady state (CR addition just equal to decay), the peak-peak radiocarbon variation is due to dilution; the global CO₂ variation is 0.5%.

Growth of trees measured by ring width can aid in establishing the thermal chronology for much of the Holocene but is a complicated function of moisture and air temperature. At high altitude tree growth may even be directly dependent upon solar irradiance rather than indirectly through air temperature [Fritts 1976]. The Campito Mt. record is from the timberline band which progresses and regresses with time. La Marche and Mooney [1967] find a timberline retreat of about 120-150 meters in timberline altitude from the altithermal till now. La Marche [1973] finds a retreat from 2500 BC till 1700 AD at Sheep Mt. (White Mts.) of about 200 meters suggesting a temperature variation of about 2.1° C based on lapse rate. In support of this La Marche [1974] finds a significant correlation between the combined central England [Lamb 1980] and Northern hemisphere [Mitchell 1961] temperature record and White Mt. timberline tree ring width from 800 to 1960 AD. $\Delta T \sim 1.5^\circ$ C vs. $\Delta W \sim 0.5$. The establishment of a true dendrochronological timberline thermometer is still to be made, but changes in the timberline Bristlecone ring growth record support a response primarily seated in temperature. La Marche [1974] discussed temperature-moisture stressing upon tree physiology, suggesting that the Campito Mt. Bristlecone pine timberline sequence records primarily thermal stressing.

Although the $\Delta^{14}\text{C}$ Maunder peaks (Fig. 2) tends to occur at Bristlecone pine minima detailed correspondence is not always good. The tree response is expected to follow solar irradiance closely while the atmospheric radiocarbon inventory varies approximately as the integrated CR flux which is suppressed by several decades and is noisy. The radiocarbon record also is likely subject to other forcings which do not correlate with tree growth. But from an average standpoint, as the radiocarbon peaks correspond to solar activity minima, their inverse (solar activity maxima) should correlate positively with tree ring thickness maxima, which is the case. This supports the inference that the trees are responding to aerial temperature rather than to some exotic forcing and that atmospheric temperature is indeed correlated with long period

solar activity. Extraction of a time-temperature record for the White Mts. from the tree record is difficult for two reasons: the uncertain physiology of the Bristlecone, their extreme antiquity, and the ever possibility that their growth is stressed by other factors than air temperature. The ~ 1000 year "half cycle" in the Bristlecone pine record reported by La Marche [1974] (his Fig. 4) also appears in the analysis of this paper. It corresponds about to the time from the Medieval warm epoch to the present [Lamb, 1982].

SOLAR VARIABILITY

Gough [1988] has reviewed characteristic times for the Sun but no specifically multi-hundred year periods are identified. It is possible to place global hydromagnetic modes conceptually within a solar context if a core magnetic field of (O) 1 gauss is admitted [Cowling 1945; Sonett 1982; Levy and Boyer 1982; Moss 1987]. Global solar Alfvén wave transit times vary only by about a factor of 10; though estimates are only qualitative they do suggest the possibility of eigenmodes corresponding to periods of perhaps 100-1000 years. However the inference that the Maunder cycle is a manifestation of chaotic behavior in the solar dynamo seems more plausible, e.g. Weiss and Cataneo 1984], though for either source model for the variability the theoretical foundation is sketchy. Such modes would have to exhibit a significant bolometric connection to account for the combined radiocarbon and Bristlecone variability. It is hardly a hypothesis but the well-known deficit in the high energy solar neutrino flux (See Wolfsberg and Kocharov [in press] for review.) does suggest that understanding of the solar core is still uncertain. Sporadic reports of solar radius variability infer a changes in solar diameter. Gilliland's [1981] work shows a maximum in solar diameter ca. 1910 corresponding to a minimum in solar activity. Moreover his results show a return to maximum in about 70-80 years suggesting a relation to the Gleissberg period. Ribes et al [in press] review the field including 18th and 19th century solar observations.

SUMMARY

The Maunder cycle appears throughout the entire 9000 year record of $\Delta^{14}\text{C}$ as 34 episodes of increases in delta radiocarbon corresponding to decreases in interplanetary modulation. The mean period, $\bar{A}_m = 269$ years but the variability is large ($\sigma = 129$ years). Corresponding cyclicity exists in the record of tree ring growth of Bristlecone pines from timberline in the White Mts. of Eastern California over the shorter period of ~ 5000 years. The tree variations are thought to arise from variability of air temperature though a direct dependence of growth upon solar irradiance has not been ruled out. The stochastic (or chaotic?) component in the Maunder period is large, making predictions of a related climate variability probabilistically and highly uncertain. Though the mean Maunder period is 269 years, the probability is 67 % that a given climatic maximum lies anywhere between 150 and 388 years. But the maxima are mediated by the 2300 year period which has a very different phase relation between inventory and source function than does the 269 year period. Indeed it may not be possible to assess phase in a fully meaningful way because of the extreme jitter in the Maunder cycle. Since both hydromagnetic (CR modulation by the solar wind) and bolometric (irradiance) variability may be correlated, our conjecture is that the solar dynamo displays chaotic behavior, though whether this will be supported by further work is uncertain.

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